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Modelling energy production flexibility: system dynamics approach

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Abstract

Article shows how system dynamics modelling (SDM) approach could be used in modelling the energy transition towards low carbon energy system. SDM can be used to combine the techno-economic and socio-technical analysis. The study considers flexibility issues related to integration of renewable energy sources. Simplified model structure is made to illustrate how flexibility as well as other socio-technical aspects might be modelled. Results of the model correspond to the behavior anticipated from the model structure. Namely, model imitates effects of technological disruption which rises the limits of intermittent power production from renewable sources which can be integrated into power system. The limits are increased stepwise, as a share of intermittent power production reaches certain threshold value, resulting in sequence of S-shaped growth. This study presents flexibility increase of a power system conceptually and more detailed study should uncover leverage points which could stimulate this increase and thus, transition to sustainable energy system.

Keywords: energy transition; energy flexibility; system dynamics modelling; low carbon energy systems; sustainable energy system

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1. Introduction

To respond to climate change mitigation, nations have to come together and acknowledge the necessity to move towards low carbon future. Ambitious goals have been set by Paris Agreement, and to reach these goals it is necessary to transform the existing fossil-based energy economy to cleaner energy economy.

Energy transition is not only a technological shift from one type to another, but it also includes changes in energy flows and in policies regulating energy systems [1]. To get a better understanding on how the energy system transition can occur, it is important to focus also on socio-technical aspects in action apart from traditional techno-economic studies [2]. Techno-economic research is often focused on finding the optimal solution, based on the optimal gains and costs, but does not consider whether this technology might be socially controversial, or that there might be conflicting values and interests between involved parties, and that existing industries most likely will try to resist to changes [2]. Socio-technical systems encompass changes in business models, institutional regulations and norms, energy user practices and technologic solutions [3].

To transform energy system towards low-carbon system, it would require integration of renewable energy sources (RES), e.g. photovoltaics and wind turbines, which are intermittent energy sources. Thus, flexibility challenge arises, when high shares of renewable energy is reached [4]. Fossil-based technologies can react quickly to changes in energy demand, but renewable technologies due to their intermittent nature holds uncertainty on whether they would be able to provide the output required by a demand [5]. While share of renewable energy is low, rapid changes in energy demand can be covered by installed capacity of fossil-based technologies, but as a share of renewables increases, also gap that should be covered increases, therefore presenting the issue of flexibility [5]. There is a limit to how much renewables can be introduced in existing technological and institutional framework. There is no single value that corresponds to every country, because existing systems differ in each country, but it is indicated that there are no technical barriers for integration of renewable energy up to 35 % [6]. In case of Finland, it was calculated that renewable energy share could even be increased up to 70 % in the existing power production system [7]. To increase renewable share even further, it would be necessary to search not only for innovative technical solutions, but also to change the existing regulatory and market frameworks [8].

Aim of this paper is to present a research method that could be used to investigate energy transition by including not only techno-economic, but also socio-technical aspects in modelling. This is a conceptual paper, not a case study. Model imitates effects of technological disruption which rises the limits of intermittent power production from renewable sources which can be integrated into power system. The limits are increased stepwise, as a share of intermittent power production reaches certain threshold value of the current limit, resulting in sequence of S-shape growth. The model includes a positive feedback decreasing unit costs of RES power production due to learning effect and a balancing feedback leading to decreasing rate of RES capacity installation as flexibility limit is approached.

2. Methodology

System dynamic modelling is used in this research to illustrate how it could be applied in modelling energy transition from fossil to RES based energy, and how flexibility aspect could be taken into account. System dynamics is a methodology for studying and managing dynamic problems in complex feedback systems. Quantitative energy models often limit their focus on techno-economic factors, but political, social and behavioral aspects are framed exogenously [9], whereas system dynamics modelling differ from other methods with its endogenous approach – understanding and modelling of the structure of a system, therefore viewing and embedding social aspects into the endogenous model structure. In this way it is possible to quantify also social and political impact on the studied system.

System dynamics modelling methodology consists of several steps:

- Defining the dynamic problem and stating the goal of the modelling;
- Creating the dynamic hypothesis, based on the structure of the studied system;
- Building the base structure of the model as a set of stocks (accumulate the flows), flows (regulate the stock level), parameters and feedback loops (connects the dependent variables);
- Validating the model;
- Testing the policies to find the most influential parameters, which can be changed to alter the problematic behavior of the system.

As this is only a conceptual study without specific case study, it addresses only the first steps of the modelling, including definition of the dynamic problem, creation of the dynamic hypothesis and creation of simple stock and flow structure of the system. Dynamic problem is that a rate of progress towards wider goal of deep decarbonization remains slow, therefore the goal of the modelling is to understand the potential dynamics of energy transition and flexibility issues related to intermittent renewable energy sources.

Fig. 1 illustrates possible structure of the model with main reinforcing and balancing loops, which could be responsible for system's behavior. In our case we only consider the most important loops to illustrate the basic dynamics for transition from fossil-based to renewable energy, therefore parameters like the total demand and the unit costs of fossil energy production were viewed as exogenous parameters and their possible endogenous loops were not considered. As can be seen, decision on which type of technology to install depends on the total demand of energy, costs of production and production elasticity, which describes the level of impact the difference in production costs have on decision making. By comparing the unit costs of electricity productions, it is decided how much power is produced from each type of technology. However, if RES-based power production approaches the flexibility limit for RES integration into power system, investments in new RES capacity cease. That can cause a gap between the total power production and the total demand, and this gap may be compensated by import or additional fossil-based capacity additions.

As fossil-based technologies are already in mature state, decrease in their specific investment costs are less probable than for RES technologies, whereas RES technologies are still developing, and learning effect can be observed, therefore the unit costs of energy production might decrease (effect of the reinforcing loop R, Fig. 1). The more RES technologies are installed and operated, the more knowledge is gained, which results in reduced production costs in the future, which in turn results in even more RES technologies installed, leading to more knowledge accumulated. The learning effect is not instantaneous, and it takes time to convert accumulated knowledge in economic benefits, therefore the delay should be considered when taking a feedback from RES-based production to unit costs of RES production (Fig. 1). Delay is also considered in the link between in the unit costs of production and ordering of new technology capacities, since it takes time before decision makers react to the changes in price, when deciding upon which technologies to install.

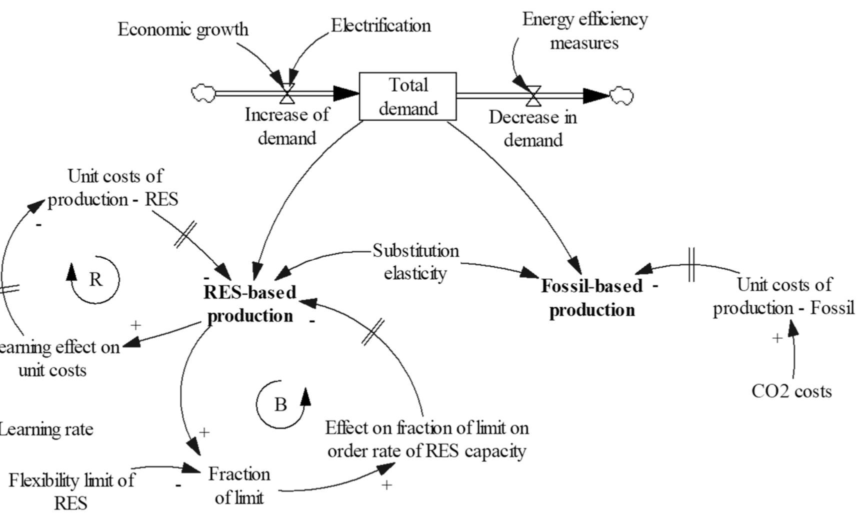

Fig. 1. Conceptual model structure; RES – renewable energy sources; R – reinforcing loop; B – balancing loop.

If there would be only reinforcing loop described above, there should be no problem for energy system to reach full decarbonization goals, but that is not the case, because current system has limits on how much intermittent RES can be integrated into the existing power system to provide a stable power system operation. Therefore, as a share of RES-based power production approached the limit the transition rate will decrease. This is portrayed by a balancing loop B (Fig. 1), which decreases the rate of order of new RES capacity.

The flexibility limit represents the current knowledge accumulated to integrate intermittent renewable energy sources into the existing system. As technologies develop and RES-based power production is approaching the flexibility limit of the existing system, rate of RES integration slows down and pressure to innovate and break these limits may become stronger. Motivation to innovate may result in partial reconfiguration of the existing regime or the existing regime might get disrupted by a new regime in which a new flexibility level has been set. For this to happen it often needs a political support and institutional changes.

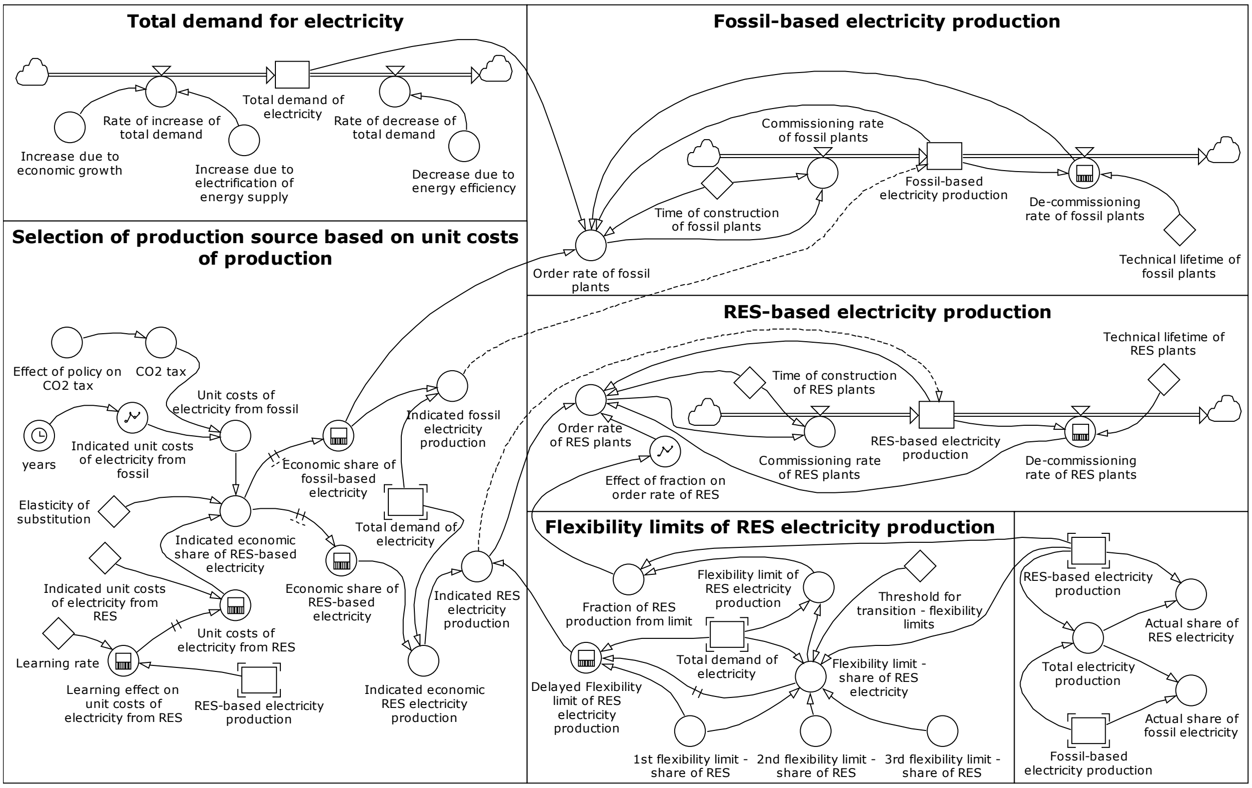

Fig. 2. Model structure illustrated with stocks and flows.

Based on the structure illustrated in Fig. 1, the stock and flow model was built (see Fig. 2) using *Powersim Studio* 10 software. Here all the stocks, flows, feedback loops and delays are incorporated, and model is formulated. Growth for unit costs of electricity production with fossil fuels are assumed to happen due to exogenous factors. The same applies to electricity demand. It is assumed that electricity demand could change due to economic growth, electrification and energy efficiency measures, but they are incorporated as exogenous elements of the system and model structure has no impact on demand growth rate. Decision regarding choice between RES or fossil-based power production is calculated by using logistic function:

$$S_f = \frac{\exp(-\alpha \cdot C_f)}{(\exp(-\alpha \cdot C_f) + \exp(-\alpha \cdot C_f)} \tag{1}$$

where

S_f share of fossil-based electricity;
C_f unit costs of electricity production from fossil resources, EUR/MWh;
C_r unit costs of electricity production from RES, EUR/MWh;
α elasticity of substitution.

Input parameters in model are not related to a specific case study and might not completely describe the real world system, but are sufficient enough to illustrate the proof of concept.

3. Results

By looking at the results in Fig. 3, it can be seen that dynamics of unit costs are exactly as described in Fig. 1. Unit costs for fossil-based electricity increases steadily, because there were no feedback loops embedded in the model, and growth is assumed to happen due to exogenous factors, while changes in unit costs for RES-based electricity are regulated by reinforcing and balancing loop.

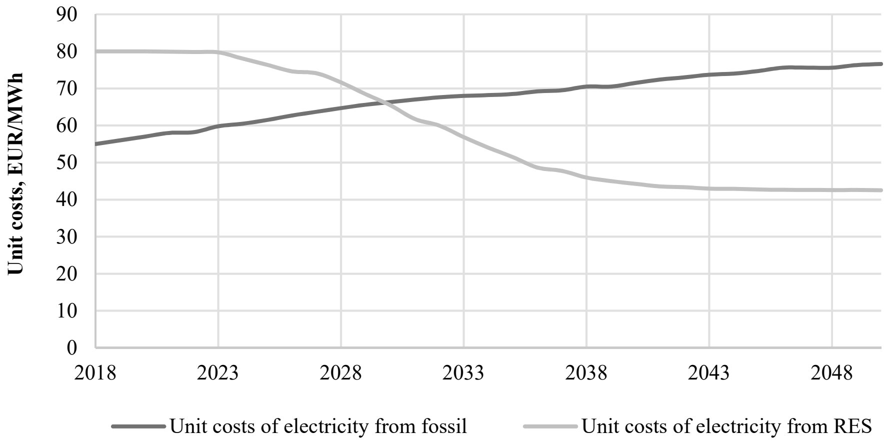

Fig. 3. Dynamics of unit costs of electricity production from fossil resources and RES.

Increasing rate of decline of unit costs for RES-based electricity production is due to learning effect. It can be seen in Fig. 4, that as more RES-based technologies replace fossil-based technologies, more capacity is installed, and more knowledge is gained, resulting in further decrease of unit costs for RES-based power production (see Fig. 3). Decline in unit costs of RES-based power production cannot continue forever, because there is a limit for improvement of certain technology within the current level of knowledge. Therefore, when approaching the maximum level of technology penetration, less new capacities are installed, and less improvements are gained leading to decline of unit costs of production.

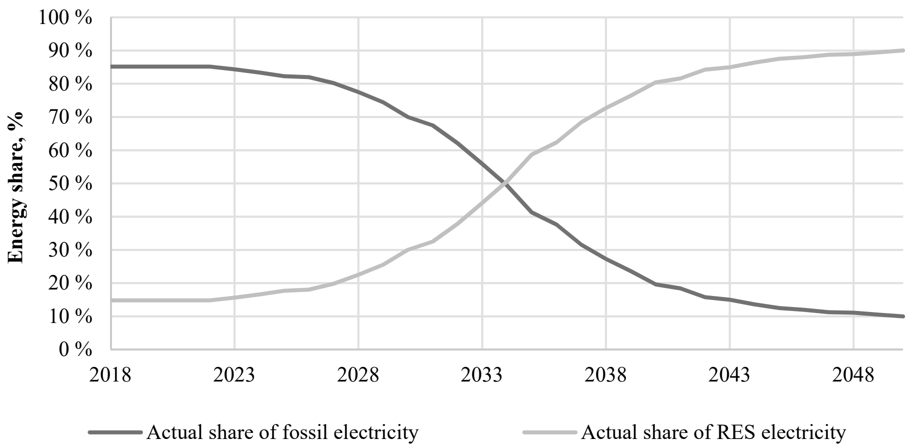

Fig. 4. Shares of fossil and RES-based power production.

Energy transition from fossil to renewable energy technologies happens gradually, not instantaneously, because investment decisions of power companies have a delayed response to changes in unit costs of technologies. In the model this is considered by elasticity of substitution. Although the unit costs of power production for RES-based technologies become less than for fossil fuel-based technologies around year 2030 (Fig. 3), it takes several years before a share of RES-based power production overtakes a share of fossil- based power production.

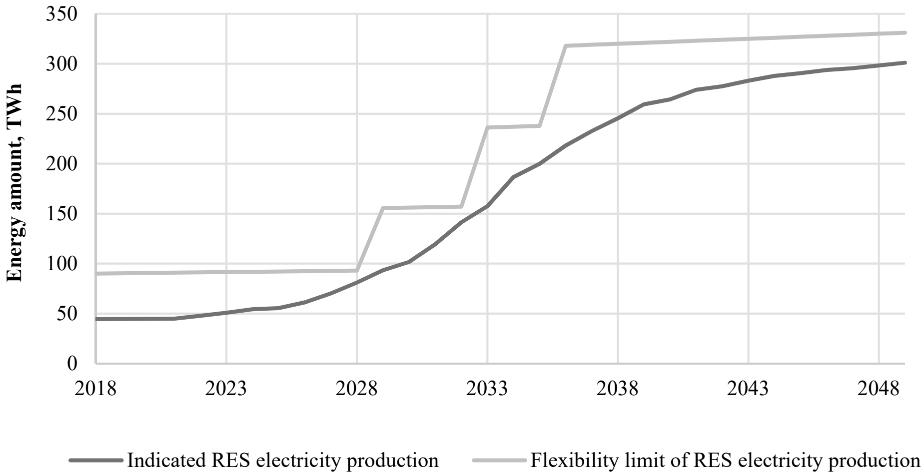

Fig. 5. Indicated RES electricity production depending on flexibility limits.

Fig. 5 illustrates dynamics of RES-based power production depending on changes in flexibility limit. When RES-based electricity production approaches flexibility limit, power companies become reluctant in investing in new RES capacities and it is necessary to innovate in order to increase flexibility limit. Technological disruption due to innovation is modelled in the following way. When a certain threshold of the share of RES-based power production is reached (i.e. 80 % of the maximum allowed by flexibility constraints) disruption leads to new increased flexibility limit. Model also shows that if the threshold value is set higher, i.e. close to 100 % of the limit, it may become impossible to reach that threshold value (due to ceased investment in RES-based power production) and no disruption takes place. That leads to a situation when RES-based power production remains under the set flexibility limit and does not increase. This effect depends on effect resulting from reaching a certain fraction of the flexibility limit on decisions to invest in new RES-based power production capacities.

4. Conclusions

Modelling results show that the structure of the model, described in Section 2 exhibits the anticipated behavior, i.e. S-shaped increase of RES-based power production due to two effects: decreased unit costs of production of RES power technologies and step-wise increase of flexibility limit resulting from potential disruption in power systems. This study presents flexibility increase of a power system conceptually and more detailed study should uncover leverage points which could stimulate this increase and thus, transition to sustainable energy system. Further research is needed to obtain more knowledge about socio-technical dynamics and build the more detailed model structure, by taking into account all the relevant feedback loops of the real-world system.

Acknowledgements

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